NON-CONTACTING COMPLIANT FOIL SEAL FOR GAS TURBINE ENGINE

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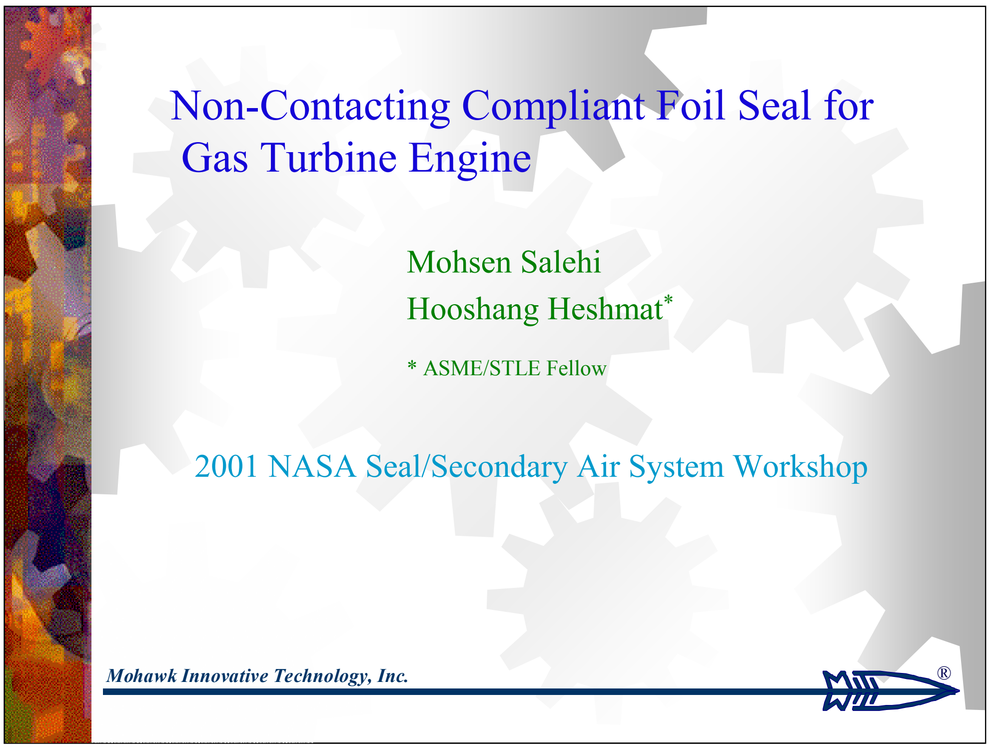

Acknowledgment

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Overview

- Objectives
- Test Facilities
- Analysis Enhancements
- Accomplishments/Status
- Materials Study
- Conclusions/Remarks

Objectives (1/2)

- Main Objective : CFS's (up to 6 in) with minimum leakage
  - Enhance the analysis to include turbulence and effect of top foil structure
  - Investigate manufacturing/fabrication processes
  - Examine segmented, split or other designs
  - Results of Phase I candidate materials review
  - Consider forming of foils with various thicknesses
  - Modify the current test rig to test the 6 " Dia. seal at speeds up to 20,000 rpm, P [0-100]
  - Accommodate ambient temperatures up to 800 °F

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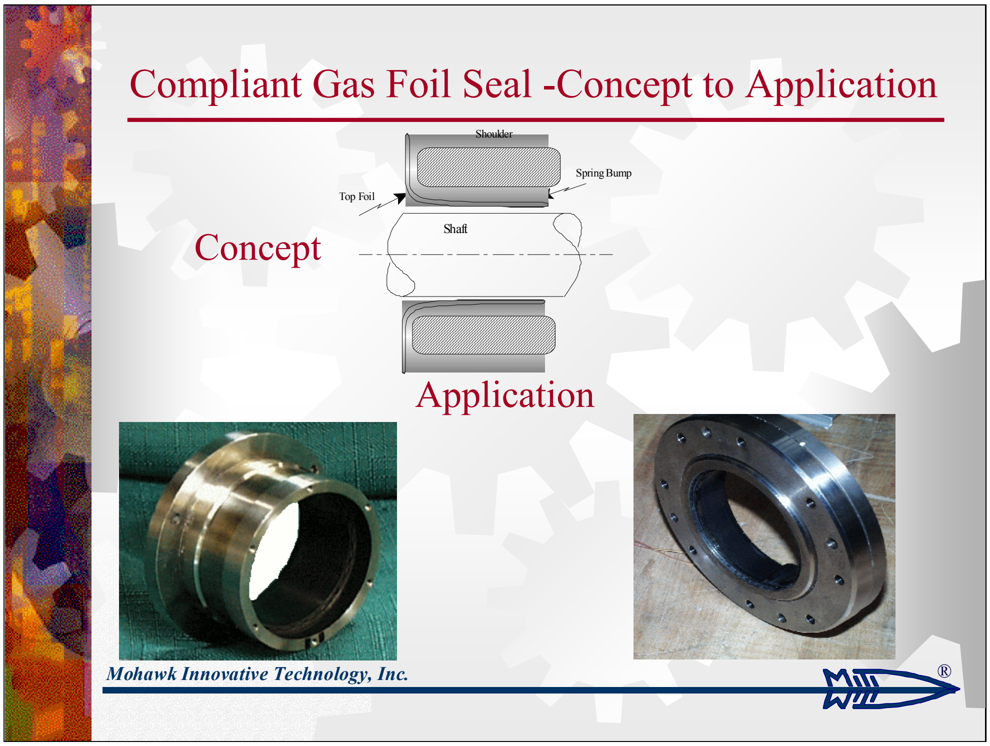
The program aimed at enhancing the existing analysis to include the turbulence effect. Several manufacturing methods are being investigated in order to apply our know-how in building the seal hardware.

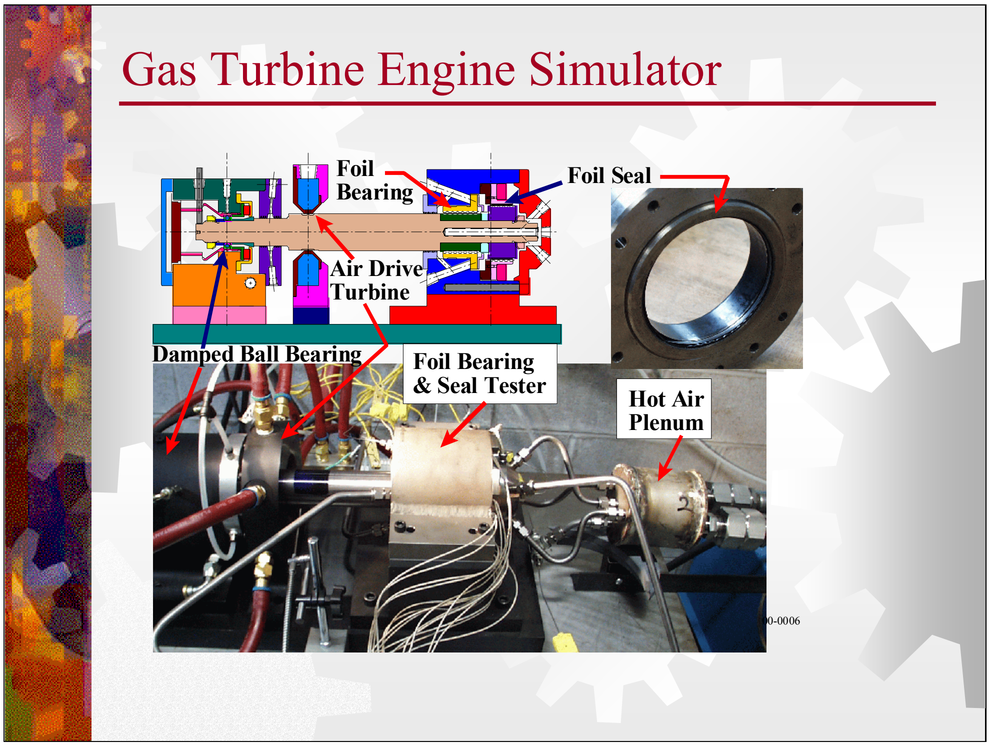
Objectives

(2/2)

- ❖ Use enhanced analysis and manufacturing results, in addition to a experimental parametric study
- ❖ Fabricate and test 6 in seal
- ❖ Build 8.5 in seal for NASA test rig



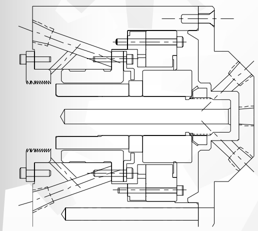
The basic concept of the seal is shown here. The two initial seal hardware built are also shown. The seal on the left side has 1.5 in diameter and the seal right side has 2.84 in diameter.



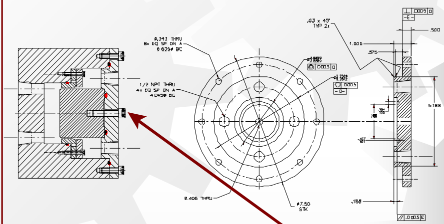
The small gas turbine engine simulator is shown here. The hybrid system included ball bearing and compliant foil bearing for support. The compliant foil seal and foil bearing were taken to speed as high as 56,000 rpm and temperature as high as 1100 F.

Small Seal Test Rig Modification

STTR Seal Test Section



Modified Seal Test Section



❖Modified Seal section for Static Test

Flat end cap

End plug

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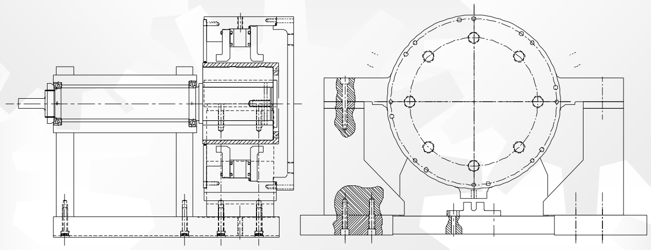
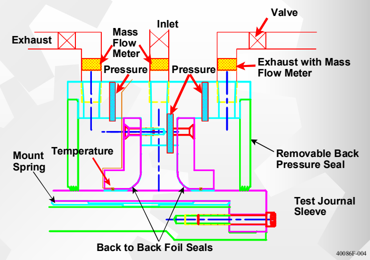
The hybrid system compliant foil seal housing (shown in previous page) was modified for quick static tests.

Subcomponent Test Rig for 6 in Seal

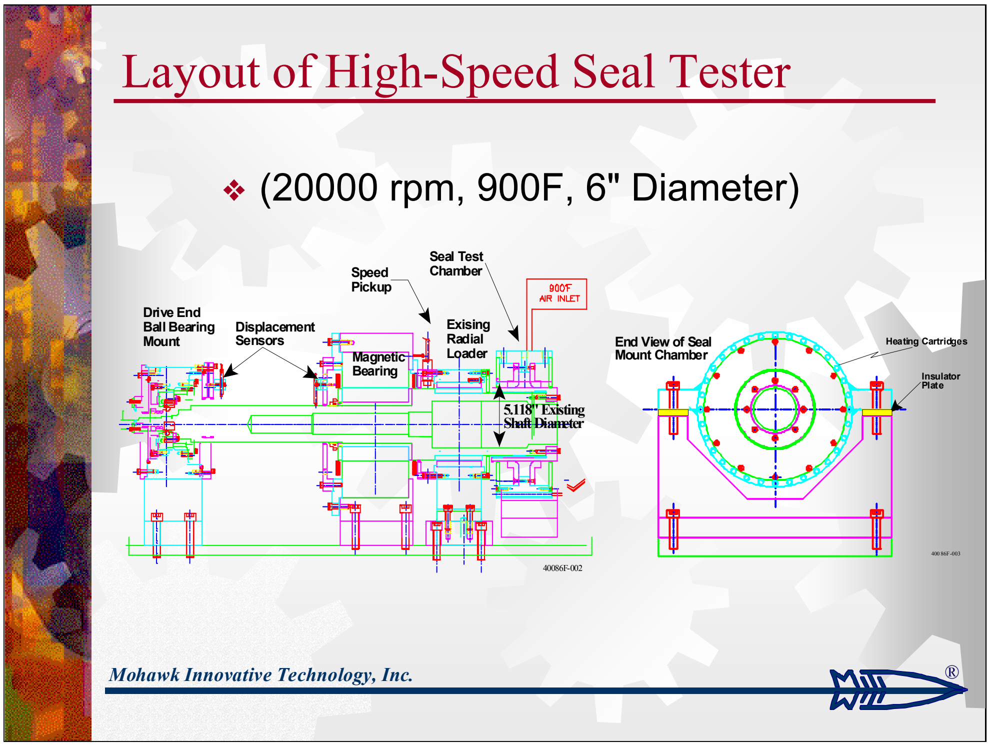
Mainly for static test, however capable of dynamic tests



Seal housing top cross section



The subcomponent test rig will be used to test the 6 in seal. Most test will be static test. However the test rig can accommodate for some limited dynamic conditions.



The main dynamic test rig is shown here. This seal tester consists of rolling element bearing and magnetic bearing for main support.

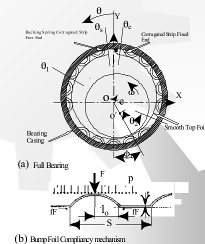
A compliant radial loader is used for control of rotor orbit. The magnetic bearing also provides testing with controlled eccentricity introduced to the seal.

Reynolds – Compliance Equations for Laminar Flow

Reynolds Equation:

Velocity & Inertia

$$\frac{\partial}{\partial \theta}\left[\bar{P}\,\bar{h}^{3}\frac{\partial \bar{p}}{\partial \theta}\right]+\frac{\partial}{\partial \bar{z}}\left[\bar{P}\,\bar{h}^{3}\frac{\partial \bar{p}}{\partial z}\right]=\Lambda\frac{\partial}{\partial \theta}(\bar{P}\,\bar{h})$$



$\bar{z} = (Z/R)$ $\bar{p} = (P/P_L)$ $\bar{h} = (h/C)$

Film Thickness :

$$\mathbf{h = C + e\,Cos\,(\theta - \theta_0) + \overbrace{\sum K_{ij}\,(p_{eff} - P_N)}^{\text{Compliancy}}}$$

K_{ij} : The combined compliancy coefficeint

P_N: Normalized pressure behind foils

Governing equations of pressure and film thickness combined with structural compliance is presented. The above equations were applied to the laminar flow conditions.

Modified Reynolds Equation for Turbulent Conditions

$$\frac{\partial}{\partial\theta}\left[G_x p^*(h^*)^3\frac{\partial p^*}{\partial\theta}\right]+\frac{\partial}{\partial z^*}\left[G_z p^*(h^*)^3\frac{\partial p^*}{\partial z^*}\right]=\Lambda\frac{\partial}{\partial\theta}\left(p^*h^*\right)$$

$$h^*=\left(\frac{h}{C}\right)=1+e\ \cos(\theta-\phi)+\sum\alpha_{i,j}(p^*-1)$$

$$|\nabla p|^*=\left((\frac{\partial p^*}{\partial\theta})^2+(\frac{\partial p^*}{\partial z^*})^2\right)^{1/2},\qquad \mathrm{Re}^*=\mathrm{Re}_r{}^*(h/C)^3|\nabla p|^*$$

$$G_z=Min\left[G_z(\mathrm{Re}),G_p(\mathrm{Re}_p)\right]$$

$$G_x=Min\left[G_x(\mathrm{Re}),G_p(\mathrm{Re}_p)\right]$$

$$\mathrm{Re}_p=\frac{h^3}{\mu\nu}\nabla p$$

$$\frac{1}{G}=\frac{1}{G_x}=\frac{1}{G_z}=1.471\left(\mathrm{Re}_p\right)^{0.681}$$

$$\frac{1}{G_x}=0.0687\mathrm{Re}^{0.75}$$

$$\frac{1}{G_z}=0.0392\mathrm{Re}^{0.75}$$

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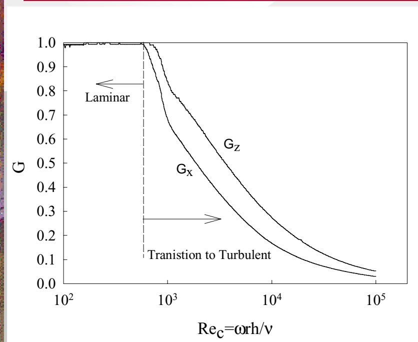
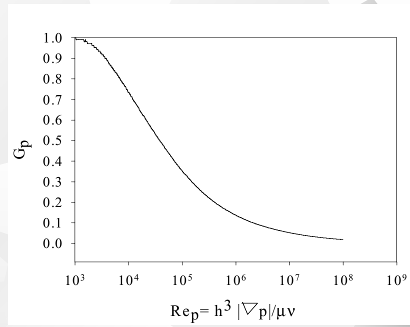
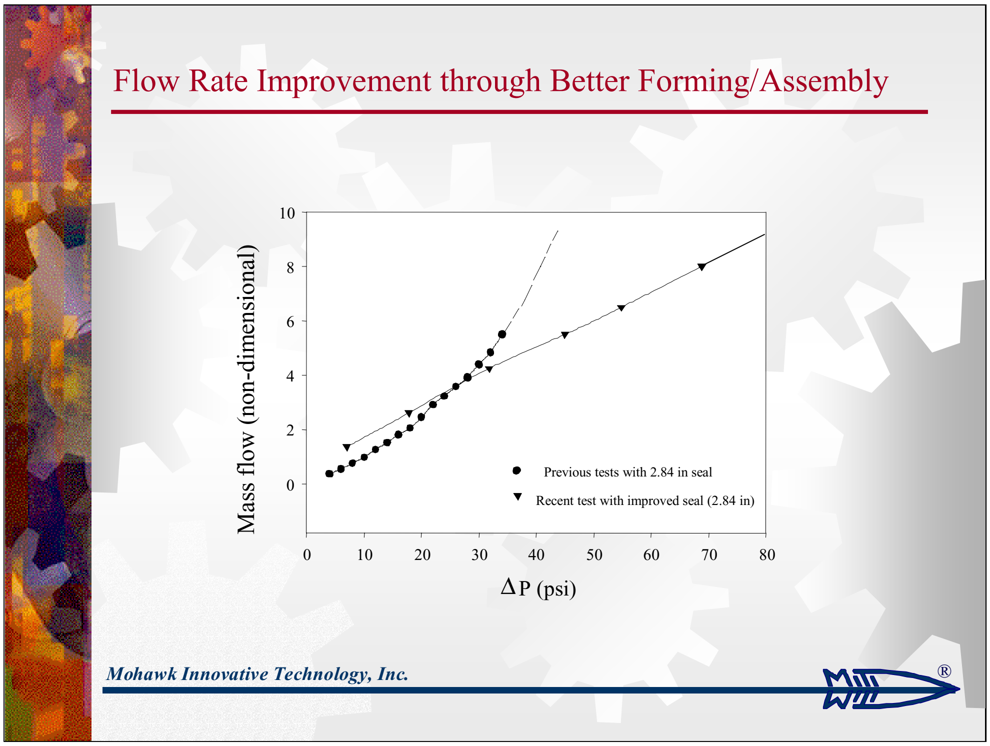
The turbulence influence was introduced via some turbulent functions (G’s). These G’s were calculated based on the circumferential Reynolds and pressure Reynolds numbers.

Turbulence Functions





Plots of G functions vs. Reynolds numbers.

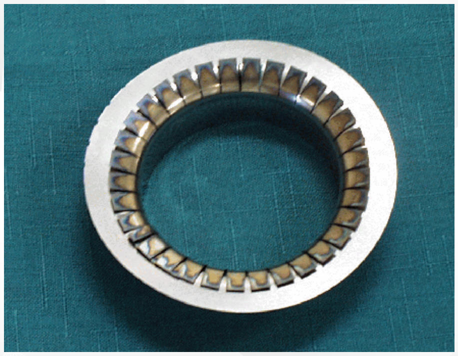


Static test showing the performance of the improved seal against the existing seal. The trend in improved seal is more linear at high pressure.

Accomplishments/Status

- Analysis enhancements is completed
- Seal manufacturing enhancement is partially fulfilled
- Materials testing matrix is finalized and preparation for testing is in process
- Small scale tested to $\Delta P = 80$ Psi conducted
- Large scale static test rig is in manufacturing/parts -delivery process
- Fabrication of high speed test rig is in process
- Implement fabrication/know-how to large size seal

Photo of Enhanced CFS



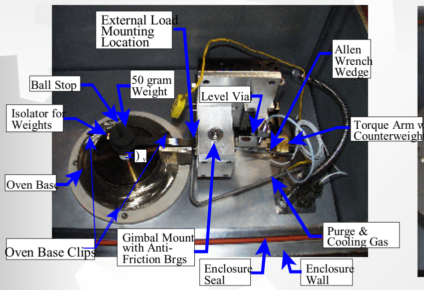
Additional foil ring is incorporated in the enhanced seal

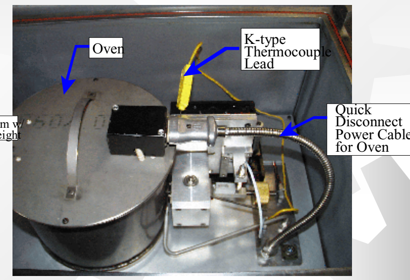
Material Study Recommendations from Ph.I

- Seal Material
  - Haynes 230, Haynes 214 (Approx. 15% Cr)
  - Waspalloy
- Journal Material
  - Pyromet alloy 600, alloy 41
  - Waspaloy
- Coating
  - PS304
  - Tungsten Carbide
  - Chromium Carbide

Material study from Phase I was revisited.

High Temperature Tribometer





Specifications
Test Configuration -Pin on disc / Pad on disc set-up
Temperature - 1500°F
Speed - 10,000rpm
Load Range - 0.22 - 1.1lb
Multi-track disc range from 0.125 to 3.135in

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The in-house high temperature tribometer is used for testing trobological characteristics of the materials to be used in seal hardware.

Test Procedures

<u>Material Characterization</u>
Foil Material - for top pad on HT Tribometer- Waspalloy
Disc Material - for HT Tribometer - Heat Treated Inconel X718

<u>Test Matrix</u>

Test No.	Test Condition	Load, psi	Speed, rpm	Test Duration, mins	
				Start-up	Shut-down
1	Ambient	2	5000	25	2
2	Ambient	2	10000	25	2
3	Ambient	3	5000	25	2
4	Ambient	3	10000	25	2
5	H/ Temp - 1200°F	2	5000	25	2
6	H/ Temp - 1200°F	2	10000	25	2
7	H/ Temp - 1200°F	3	5000	25	2
8	H/ Temp - 1200°F	3	10000	25	2

The selected materials and test conditions are shown here.

Test Procedures

- Foil seal simulation

  Foil Material - for top pad on HT Tribometer- Waspalloy

  Disc Material - for HT Tribometer - Heat Treated Inconel X718

- Tribomaterial

  Surface will be examined to characterize the type of wear using a High Powered Zeiss MC63 Microscope

Conclusions/Remarks

- Non-Contact compliant foil seal is under development for structural integrity and performance evaluation
- Analysis included the turbulence effects
- Differential pressure up to 80 Psi was statically tested
- Dynamic and static test rigs are under development
- Material study aims at addressing the tribological concerns
- Manufacturing process and forming techniques are applied for better performance of the seal
- Structural integrity of the large seal should be address in future